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6. AUTHOR(S)
Dr. E. Fred Schubert, Professor of Engineering, Boston University

8 Saint Mary's Street Boston MA 02215

Phone 617-353-1910 Email EFSchubert@bu.edu

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Boston University, 10 Buick Street, Boston MA 02215

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9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Dr. Colin E. C. Wood
Electronics Division
800 North Quincy Street
Arlington VA 22217-5660
Email WoodC@onr.navy.mil

Program Officer
Office of Naval Research
Ballston Tower One
Phone 703-696-4218

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14. ABSTRACT
Gallium nitride (GaN) and related compounds are wide bandgap semiconductors suited for high power transistors and many other electronic and optoelectronic devices operating at high frequencies and elevated temperatures. A characteristic of GaN and related compounds is a high activation energy of acceptors, which leads to a low hole concentration in and high p-type resistivity of these materials. The present project proposed and demonstrated a novel approach to the well-known doping problem in GaN. This approach, called "superlattice doping" uses thin layers of materials with different compositions and bandgap energies. As a result, acceptors exhibit a substantially higher activation and, as a result, the p-type conductivity is strongly enhanced. Under the project, AlGaN / GaN superlattices were demonstrated with resistivities that are a factor of ten lower than resistivities of p-type GaN. The properties of the superlattices, including the design, acceptor activation energy, resistivity, temperature dependent hole concentration and mobility, spatial carrier distribution, and optical properties were investigated and the results are presented.

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Dr. Colin E. C. Wood

Program Officer

Electronics Division

Office of Naval Research

800 North Quincy Street

Ballston Tower One

Arlington VA 22217-5660

Phone 703-696-4218, Email WoodC@onr.navy.mil

By

Dr. E. Fred Schubert

Professor of Electrical Engineering

Boston University

8 Saint Mary's Street

Boston MA 02215

Phone 617-353-1910, Email EFSchubert@bu.edu

20020415 051

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Executive summary

Gallium nitride (GaN) and related compounds are wide bandgap semiconductors suited for high power transistors and many other electronic and optoelectronic devices operating at high frequencies and elevated temperatures. An unfortunate characteristic of GaN and related compounds is a high activation energy of acceptors, which leads to a low hole concentration and high p-type resistivity of these materials. High resistivities result in parasitic resistances that are detrimental to the performance of practically all devices. For example, in bipolar transistors, parasitic resistances lead to a reduction in output power, power-added efficiency, 3 dB frequency, high-temperature capability, and reliability.

The present project concerned a novel approach, called *superlattice doping*, to solve the well-known doping problem in GaN. This approach, first proposed by the Principal Investigator (PI) in 1996, uses thin layers of different materials, for example an AlGaN / GaN superlattice. The superlattice is also doped with acceptors. As a result of the potential modulation, a much higher percentage of acceptors is activated. Whereas typical activation efficiencies in p-type GaN are about 5 %, the activation efficiency in AlGaN / GaN superlattices can be as high as 80 %. Therefore, the p-type conductivity is enhanced. Under this project, AlGaN / GaN superlattices were demonstrated with resistivities less than 0.2 Ohm cm at room temperature and less than 0.1 Ohm cm at cryogenic temperatures. Typical p-type GaN resistivities are about 1 Ohm cm at room temperature. Thus superlattices represent a factor of 5 to 10 improvement over bulk GaN.

The properties of the superlattices, including the design, acceptor activation energy, resistivity, temperature-dependent hole concentration and mobility, spatial carrier distribution, and optical properties have been investigated. The acceptor activation energy is reduced to values < 50 meV as compared to values of 200 meV for bulk GaN. Hole concentrations in the 10^{18} cm^{-3} range are typical for the superlattices. Hole mobilities of 8 cm^2 / Vs have been found in modulation-doped AlGaN / GaN superlattices grown by MBE. This value compares favorably with hole mobilities of 0.3 cm^2 / Vs found in the highly doped p-type GaN grown by MBE. The spatial carrier distribution is analyzed by C-V measurements. The profiles show two clear peaks in the hole concentration indicating the two-dimensional (2D) character of the hole distribution and the formation of 2D hole gases in the superlattice.

Brief statement on advances made under ONR grant

- Enhancement of hole concentrations by approximately one order of magnitude in p-type AlGaN / GaN doped superlattice structures as compared to p-type bulk GaN.
- Reduction of acceptor activation energy from 200 meV in p-type bulk GaN to < 50 meV in AlGaN / GaN doped superlattice structures.
- Strong reduction of the temperature dependence of the resistivity on the temperature range 100 K to 400 K in AlGaN / GaN doped superlattice structures as compared to p-type bulk GaN.
- Additional advantage of high mobility is realized in modulation doped AlGaN / GaN superlattice structures. Mobilities of 8 cm^2 / Vs in MBE grown superlattices and 20 cm^2 / Vs in OMVPE grown superlattices have been found. This compares well with the bulk mobilities of p-type GaN. In heavily doped p-type GaN, hole mobilities are as low as 0.3 cm^2 / Vs.
- During the project, an invention was made that has great potential to improve ohmic contact technology in III-Nitrides. The novel contact technology uses the polarization-effect in cap layers thereby decreasing the tunnel barrier thickness and specific contact resistance.
- Analysis of the optical properties of the superlattices has confirmed the presence of polarization fields.
- The program also had a substantial positive effect on the education of both Master and Ph.D students. The program has allowed support of the persons: John Graff (Ph.D), Yun-Li Li (Master and Ph.D.), Jay Shah (MS), Erik Waldron (Ph.D.), and Thomas Gessmann (post doc).

List of publications and patents arising from this ONR funding

Goepfert I. D., Schubert E. F., Osinsky A. and Norris P. E. "Demonstration of efficient p-type doping in AlGaN / GaN superlattice structures" *Electronics Letters* **35**, 1109 (June 1999)

Goepfert I. D., Schubert E. F., Osinsky A., and Norris P. E. "Efficient acceptor activation in AlGaN/GaN doped superlattices" accepted by the *MRS Internet Journal Nitride Semicond. Research, see* http://nsr.mij.mrs.org/5S1/W3.85/ (March 2000)

Li Y.-L., Schubert E. F., Graff J. W., Osinsky A., and Schaff W. "Low-resistance ohmic contacts to p-type GaN" *Appl. Phys. Lett.* **19**, 2728 (May 2000)

Goepfert I. D., Schubert E. F., Osinsky A., Norris P. E., and Faleev N. N. "Experimental and theoretical study of acceptor activation and transport properties in *p*-type $Al_xGa_{1-x}N$/GaN superlattices" *J. Appl. Phys.* **88**, 2030 (Aug. 2000)

Chernyak L., Osinsky A., Fuflyigin V., and Schubert E. F. "Electron-beam induced increase of electron diffusion length in p-type GaN and AlGaN/GaN superlattices" *Appl. Phys. Lett.* **77**, 875 (Aug. 2000)

Graff J. W., Schubert E. F., Osinsky A., "On the reduction of base resistance in GaN-based heterojunction bipolar transistors" Proceedings of the 2000 IEEE / Cornell Conference on High-Performance Devices, p. 28, ISBN 0-7803-6381-7 (Oct. 2000)

Waldron E. L., Schubert E. F., Graff J. W., Osinsky A., Murphy M. J., and Schaff W. F. "Evidence of polarization effects in doped AlGaN / GaN superlattices" Proceedings of MRS Fall Conference (Dec. 2000)

Graff J. W., Schubert E. F., and Osinsky A. "GaN / SiC mesa junctions for HBTs fabricated using selective photoelectrochemical etching" *Electronics Letters* **37**, 249 (Feb. 2001)

Chernyak L., Osinsky A., Fuflyigin V., Graff J., and Schubert E. F. "Minority Electron Transport Anisotropy in p-type $Al_xGa_{1-x}N$/GaN Superlattices" *IEEE Transactions on Electron Devices* **48**, 433 (March 2001)

Waldron E. L., Graff J. W., and Schubert E. F. "Improved mobilities and resistivities in modulation doped p-type AlGaN / GaN superlattices" *Appl. Phys. Lett.* **79**, 2737 (Oct. 2001)

Waldron E. L., Graff J. W., and Schubert E. F. "Influence of doping profiles on p-type AlGaN/GaN superlattices," *Physica Status Solidi (A)* **188**, 889 (Nov. 2001)

Li Y.-L., Graff J. W., Waldron E. L., Gessmann T., and Schubert E. F. "Novel polarization enhanced contacts to *n*-type GaN" *Physica Status Solidi (A)* **188**, 359 (Nov. 2001)

Gessmann T., Li Y.-L., Waldron E. L., Graff J. W., and Schubert E. F. "Ohmic contacts to p-type GaN mediated by polarization fields in thin InGaN capping layers" *Appl. Phys. Lett.* **80**, 986 (Feb 2002)

Graff J. W., Li Y.-L., and Schubert E. F., "Low-resistance metal-semiconductor ohmic contacts to p-type GaN using polarization effects", invention disclosure filed with Boston University in Dec. 1999, provisional patent application, filed with PTO in March (2000)

Detailed discussion of work

Introduction

The achievement of high p-type conductivity in many wide-bandgap semiconductors is difficult due to the large acceptor binding energies. In the case of III-V nitrides, the acceptor effective Rydberg energies are 200 to 400 meV for commonly used acceptors such as Mg and Zn. In the freeze-out regime, the free hole concentration in a semiconductor with acceptor concentration N_A and acceptor binding energy E_a is given by

$$p = \sqrt{\frac{1}{g} N_A N_v} \exp\left(-\frac{E_a}{2kT}\right)$$

where g is the acceptor degeneracy, N_v is the effective density of states at the valence band edge, and kT is the thermal energy. For an acceptor energy of 200 meV, the electrical activation calculated from the above equation is 5 % at room temperature.

To overcome the fundamental problem of low acceptor activation, a ternary compound semiconductor structure with a spatially modulated chemical composition had been proposed (Schubert *et al.*, 1996). The modulation of the chemical composition leads to a variation of the valence band energy and results in a strong enhancement of the acceptor activation.

The band diagram of a uniformly doped, composition-modulated semiconductor structure is shown in ***Fig.*** 1(a). It is assumed that the acceptor effective Bohr radius is much smaller than the period of the superlattice, so that the acceptor levels in the barriers are not influenced by adjacent wells and vice versa. For an effective mass of $m_h^* = 0.8\ m_0$, the effective Bohr radius calculated for hydrogenic impurities is 6 Å, *i. e.* smaller than the period of the superlattice considered. ***Fig.*** 1(b) schematically shows the free carrier concentration in the valence band. The hole concentration is modulated and follows the modulation of the valence band edge.

Under the ONR sponsored program, superlattices were designed and the properties were assessed. The superlattices were grown by epitaxy in a collaborative effort with other groups working in the field. These groups included Cornell University, Pennsylvania State University, National Central University (Taiwan), NZ Technologies Corporation, ATMI Corporation, and SVT Corporation.

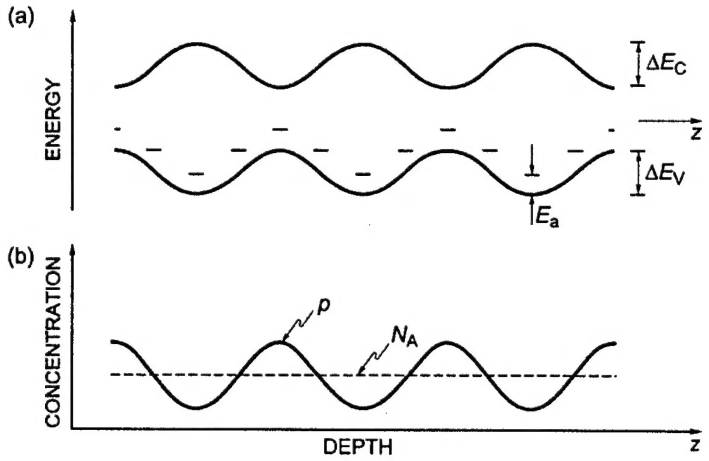

Fig. 1. (a) Schematic band diagram of a "straddled lineup" semiconductor superlattice with a modulated chemical composition. (b) Doping concentration N_A, and hole concentration p.

Increased hole concentrations

The carrier concentrations in bulk p-type GaN and in p-type AlGaN / GaN superlattices were measured as a function of temperature using the Hall effect. The superlattice samples consist of 20 periods. The well and barrier thickness are 10 nm and 10 nm. Superlattices with two different Al mole fractions, namely 10 % and 20 %, were investigated.

The hole concentration as a function of reciprocal temperature is shown in ***Fig***. 2, along with a p-type bulk GaN sample. Inspection of the figure shows several important differences between the bulk and the superlattice samples. *First*, the hole concentration in the superlattices is significantly higher than in the bulk GaN sample. *Second*, the dependence of the hole concentration on temperature is much weaker for the superlattice samples. *Third*, the hole concentration on the sample with the higher Al content is higher, consistent with the expectation that a larger potential modulation will lead to a higher hole concentration.

The superlattice sample containing 20 % Al in the barriers, has a free carrier concentration of nearly 10^{19} cm^{-3} at 400 K. This is one of the highest hole concentrations achieved in any p-type GaN structure.

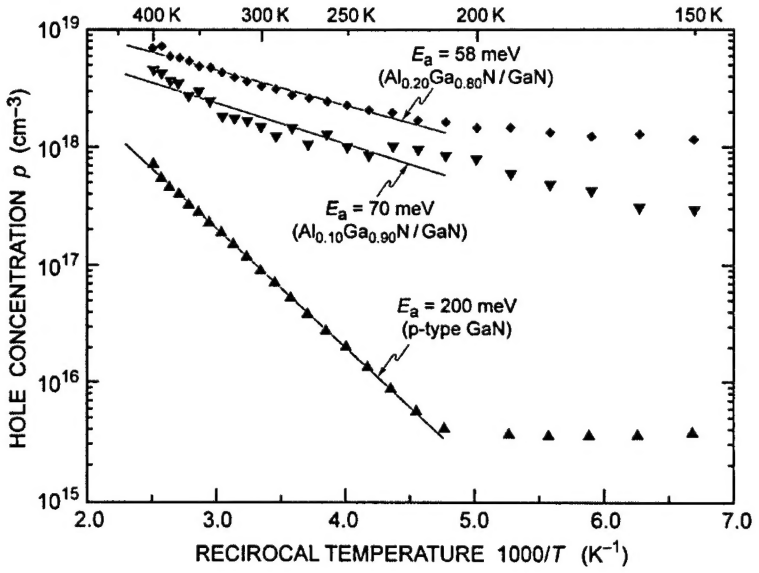

Fig. 2. Hole concentration of an AlGaN / GaN superlattice with 10 % Al content, an AlGaN / GaN superlattice with 20 % Al content, and of bulk p-type GaN versus reciprocal temperature.

Improved acceptor activation energies

The acceptor activation energy in semiconductors is usually evaluated according to the formula

$$p \propto \exp(-E_A / kT) .$$

Strictly speaking, there are different formulas for compensated semiconductors, where the above equation applies and uncompensated semiconductors, where the factor of kT is replaced by $2kT$. However, since the "kT" formula (rather than the "$2kT$" formula) is commonly used, it is also used here to determine the activation energy.

The activation energy of the superlattice structures shown in ***Fig.*** 2 is 70 and 58 meV for the superlattice containing 20 % and 10 %, respectively. The activation energy on samples investigated more recently was generally below 20 meV. This activation energy is much lower than the activation energy obtained for p-type bulk GaN where an activation energy of about 200 meV is measured, as shown in ***Fig.*** 2. Furthermore, the lower activation energy is measured

for the superlattice having a higher percentage of Al in the barriers, again, consistent with the expectation that a larger potential modulation will result in a lower activation energy.

Lowered resistivities

The lowest resistivities were found in samples that were not uniformly doped but rather modulation doped. The effect of modulation doping in $Al_{0.20}Ga_{0.80}N$ / GaN superlattices was investigated using Hall-effect and *C-V* profiling techniques. Mobility, resistivity, and carrier concentration are measured as a function of temperature.

Modulation-doped (MD) and shifted-modulation-doped (SMD) samples were investigated and have superior electrical properties compared to uniformly doped (UD) samples, especially at low temperatures.

The Mg-doped gallium-faced superlattices (SLs) were grown by molecular-beam epitaxy (MBE) on *c*-plane sapphire substrates. All doped regions have a Mg concentration of $N_{Mg} \approx 10^{19}$ cm^{-3} and all samples have an equal barrier and well width of 10 nm. The MD, SMD, and UD samples have 20, 20, and 15 periods respectively. Only the barrier layers of the MD sample are doped whereas the well layers are undoped. The SMD sample is identical to the MD sample except that the SMD dopants are shifted one-quarter period away from the epilayer surface. The UD sample has both the $Al_{0.20}Ga_{0.80}N$ barrier and GaN well layers doped.

The resistivity of the SL samples as a function of temperature is shown in ***Fig.*** 3. There is an improvement for the MD and SMD SL compared to the UD SL. At 300 K, the resistivity is 0.20 Ω cm for the MD SL. The lowest resistivity of the MD SL occurs at 90 K and is 0.068 Ω cm, the lowest reported resistivity for p-type GaN and $Al_xGa_{1-x}N$ material. ***Table*** 1 contains selected resistivity values. Particularly noteworthy is the resistivity of the MD and SMD SL, which is lower than the UD SL at all temperatures and decreases monotonically with decreasing temperature, not exhibiting any freeze-out effect. This is due to the modulated valence band causing dopants to be ionized nearly independently of temperature. The improved resistivities demonstrated are beneficial for the operation of GaN-based devices operating over a wide temperature range and underscore the importance of AlGaN / GaN superlattices.

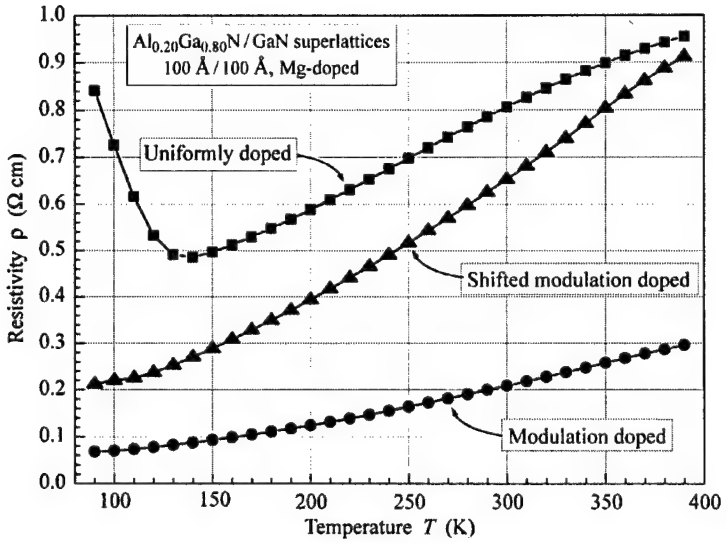

Fig. 3 Variable temperature resistivity data of a modulation-doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattice, a shifted-modulation-doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattice, and a uniformly doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattice.

	Modulation-doped	Shifted-modulation-doped	Uniformly-doped
300 K Mobility (cm^2/V s)	8.9	5.6	3.0
90 K Mobility (cm^2/V s)	36	18	2.0
300 K Resistivity (Ω cm)	0.21	0.66	0.81
90 K Resistivity (Ω cm)	0.068	0.21	0.84
300 K Hole conc. ($\times 10^{18}$ cm^{-3})	3.4	1.7	2.6
90 K Hole conc. ($\times 10^{18}$ cm^{-3})	2.5	1.6	3.7
Activation energy (meV) T = 250 to 390 K	16	13	30

Table 1. Hall-effect data of p-doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattices.

Increased hole mobilities

Consistent progress has been made in terms of the hole mobility of the superlattices. Whereas the first generation superlattices had mobilities of 1 to 2 cm^2 / Vs, later generations of superlattices had mobilities much higher than that. In MBE grown superlattices, the highest mobility measured was 8 cm^2 / Vs and in OMVPE grown superlattices, the highest mobilities were 20 cm^2 / Vs. In this report, we concentrate on the most recent data.

Fig. 4 shows the hole mobilities of the three SL structures as a function of temperature. Inspection of the figure shows a large improvement in mobility for the modulation doped (MD) and shifted modulation doped (SMD) SL versus the undoped (UD) SL, especially at low temperatures. Values of the hole mobility at selected temperatures are given in ***Table*** I. The mobility of the MD and SMD SLs continues to increase monotonically with decreasing temperature, indicative of the reduced influence of ionized impurity scattering and the presence of a 2DHG. The peak at 150 K and subsequent decrease in mobility for lower temperatures in the UD SL is characteristic of impurity scattering. All samples show a reduction of mobility at higher temperatures due to a combination of polar optical phonon scattering (Fröhlich interaction), acoustic phonon scattering, and piezoelectric scattering. Because the GaN family is strongly polar and AlGaN / GaN superlattices contain strong polarization fields, polar optical phonon scattering is expected to be the dominant scattering mechanism at temperatures above about 150 K.

The reduction of neutral impurity scattering in the MD and SMD SL is expected since their 2DHG channels contain no intentional Mg dopants. The neutral dopants in the UD SL channels is shown to cause a sharp decrease in mobility at low temperatures $\propto T^{3/2}$. Note that the MD SL exhibits a clearly higher mobility and lower resistivity than the SMD SL sample.

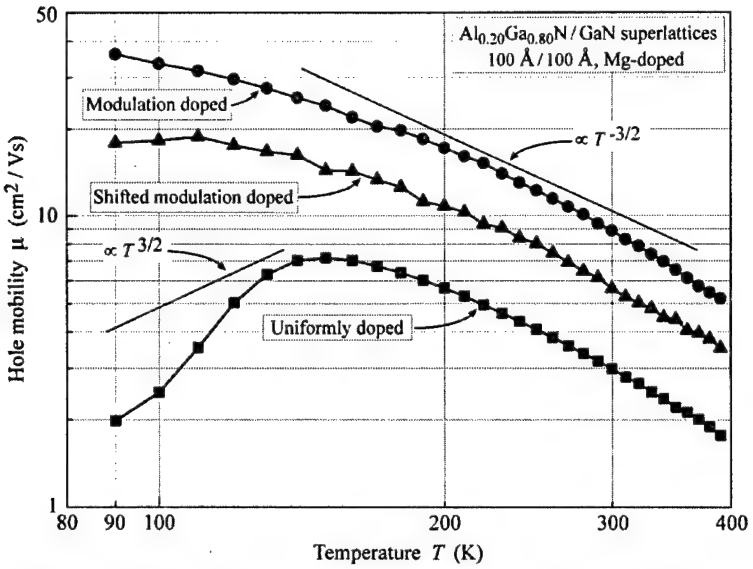

Fig. 4 Variable temperature hole mobility of a modulation-doped, a shifted-modulation-doped, and a uniformly doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattice. Straight lines with $T^{3/2}$ and $T^{-3/2}$ dependencies represent impurity scattering and polar optical phonon scattering, respectively.

Spatial distribution of carriers

It is very desirable to spatially resolve the hole concentration in superlattices. The capacitance-voltage technique offers the possibility to measure the free carrier profile in superlattices. However, C-V measurements require a rectifying Schottky contact and an ohmic contact. An alternative is the mercury probe technique. However, even with that technique, the series resistance of p-type nitride makes it difficult to determine the C-V profile. C-V profiles need to be carried out at low frequency, in the kHz range, in order to lead to viable results. Despite these difficulties, several C-V measurements on p-type superlattices were successful.

Capacitance-voltage measurements on an AlGaN / GaN superlattice are presented in ***Fig.*** 5. The C-V profile clearly shows the presence of a 2DHG with a peak at 390 Å and a FWHM of 41 Å. This corresponds to a 2D hole concentration of $\sim 4.9 \times 10^{13}$ cm^{-2}. The 2D hole density is in good agreement with the 300 K Hall value of 6.7×10^{13} cm^{-2}. The second peak at 690 Å shows the periodicity of the superlattice. At positions greater than about 800 Å C-V data cannot be obtained due to breakdown of the Hg probe Schottky contact.

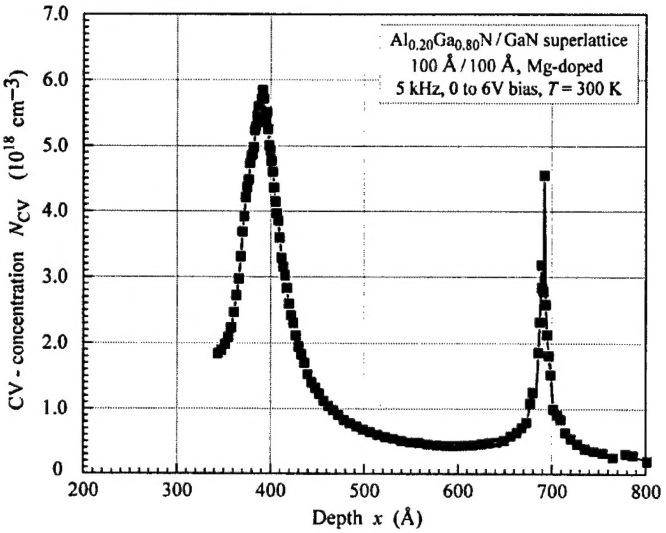

Fig. 5 *C-V* concentration profile, $N_{C\text{-}V}$, versus depth of shifted-modulation doped $Al_{0.20}Ga_{0.80}N$ / GaN superlattice.

Novel Optical properties

We have shown the first experimental evidence of multisubband photoluminescence (PL) in p-type modulation-doped AlGaN / GaN superlattices (SLs), whose low-temperature electrical properties are among the best reported to date. Hall effect measurements show a free hole concentration of 2.5×10^{18} cm^{-3} in the SL sample at 90 K. Low temperature PL spectra from a modulation-doped $Al_{0.20}Ga_{0.80}N$/GaN superlattice show multiple, well-resolved, interband transitions between quantum-confined states, as shown in ***Fig.*** 6. Besides the ground-state to ground-state transition, a number of excited-state transitions are also observed due to the inverse dependence of subband population and oscillator strength. Such PL spectra have not been observed previously in AlGaN / GaN quantum well structures.

Self-consistent calculations are used to assign transition energies and oscillator strengths to each peak making up the photoluminescence spectra. The energies are indicated in ***Fig.*** 6. The energies were calculated by solving the Poisson-Schrödinger system of equations self-consistently using the method of finite differences. The energies and wave functions of the electron and hole subbands are calculated from the 1D single-particle effective mass envelope

function Schrödinger equation. Several high-energy transitions are above the bulk bandgap of GaN. The energy shift is due to band filling and the strong dependence of oscillator strength on energy.

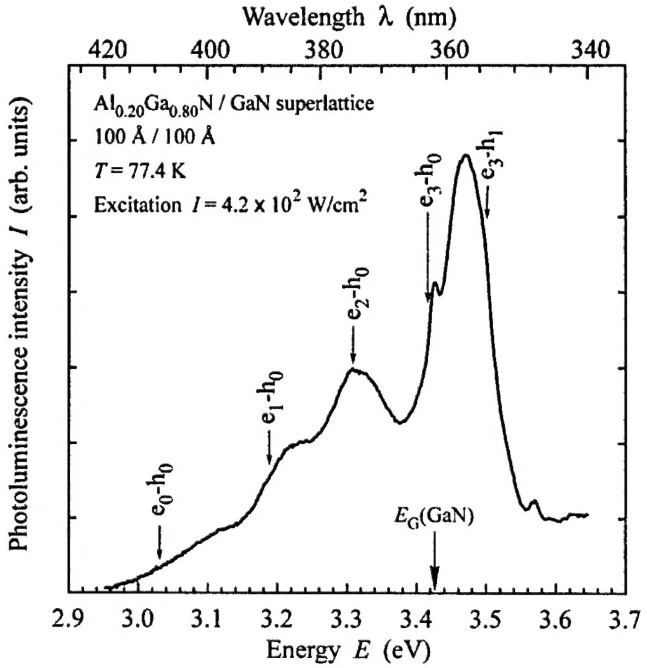

Fig. 6. Selected photoluminescence spectrum showing theoretical transition energies using theory and band diagram calculations described above. Spectra show clearly resolved subband transitions in good agreement with calculated transition energies

Self-consistent modeling

The band diagrams of AlGaN / GaN superlattices have been calculated using numerical methods. The calculation takes into account spontaneous and piezoelectric polarization effects occurring in III-Nitrides. The calculations are carried out for Ga face structures which is the polarity of the epilayers investigated under this program.

The band diagrams shown in ***Fig.*** 7 are calculated self-consistently using a 1-D Schrödinger-Poisson solve. An $Al_xGa_{1-x}N$ hole mass of $(1.76 + 1.77\ x)\ m_{ez}$, valence band discontinuity of $0.3\ \Delta E_g$, and energy gap $E_g(x) = (3.425 + 2.71\ x)$ eV is used, x being the aluminum concentration. The hole probability density is shown in Fig. 7 for each type of SL. At 90 K,

only the ground states are occupied. The Mg ionization energy in AlGaN is not known precisely. However, recent results have shown that the ionization energy of Mg acceptors in $Al_xGa_{1-x}N$ may increase from 170 meV to 360 meV for $x = 0$ to $x = 0.27$, respectively.

Fig. 7 shows the overlap between the carrier wave function and the doped regions (shaded). Inspection of the figure reveals that the shifted modulation doped structure has the smallest overlap between free carriers and dopants. The modulation doped structure (doping of barriers only) also has a rather small overlap. The figure clearly shows that all the structures have no overlap between the free carriers and *ionized* acceptors. Thus they should all have high mobilities. This is indeed found experimentally, as discussed in a previous section of this report. Furthermore, both the modulation-doped (MD) and the shifted-modulation doped (SMD) structures have very little or no overlap between the free carriers and the neutral dopants. They should therefore have better mobilities at low temperatures, which we have also discussed previously.

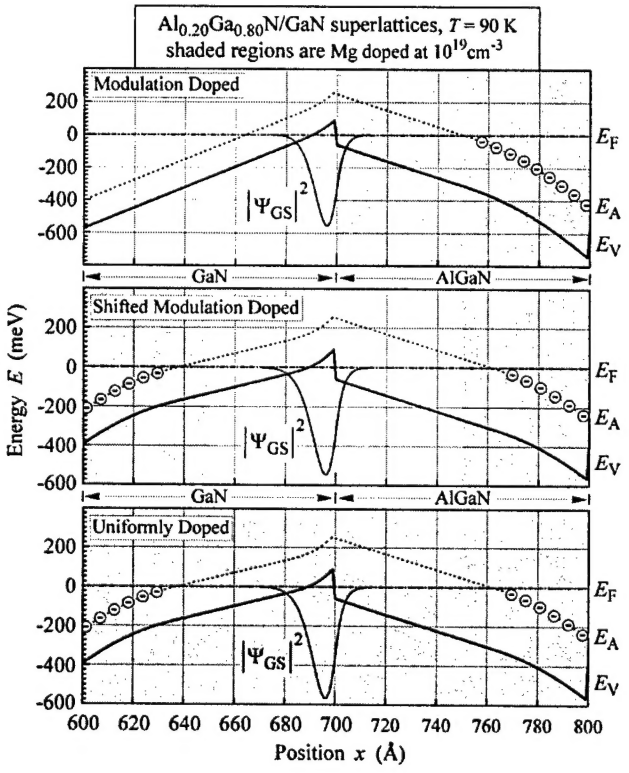

Fig. 7. Self-consistent valence band diagrams of a modulation-doped AlGaN / GaN superlattice, a shifted-modulation-doped superlattice, and a uniformly doped superlattice.

The three ground state hole energies are $E_0 - E_F = -5.9, -1.7$, and -1.7 meV, respectively. $|\Psi_{GS}|^2$ is the self-consistently solved ground-state wavefunction. It is the only occupied subband at 90 K. The epilayer surface is on the left side of the figure and a Ga face polarity is assumed.